An Overview of Power Quality Enhancement Techniques Applied to Distributed Generation in Electrical Distribution Networks

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***Abstract* – It is obvious that power quality is an important characteristic of today's distribution power systems as loads become more sensitive on the other hand nonlinear loads are increasing in the electrical distribution system. Considering the distributed nature of harmonic loads, the need for distributed power quality improvement (PQI) is inevitable. From years ago, researchers have been working on various kinds of filters and devices to enhance the overall power quality of power system, but today the nature of distribution system has been changed and power electronic based DGs play an important role in distribution grids. In this paper, a thorough survey is done on power quality enhancement devices with emphasis on ancillary services of multi-functional DGs. A literature review is also done on microgrids concept, testbeds and related control methods. Although there were some applications of DGs for PQI improvement these applications were not defined multi-functional DGs. Various control methods are studied and categorized regarding different viewpoints in the literature. Finally, a couple of thorough comparisons are done between the available techniques considering the nature, capabilities, advantages and implementation costs.**

***Index Terms* _** Power Quality, Distributed Generation, Multifunctional DGs, Microgrids, Renewable energy sources

1. Introduction

The concept of power quality is defined as the capability of the electricity grid to provide costumers reliable, ideal and non-tolerant electricity. In details power quality issues can be classified into several levels. Initially, it was just referring to the availability of electrical power, voltage and frequency regulation within a specific range [1]. As electrical devices are getting more sensitive, costumers are becoming more aware, and power quality pollutions are increasing in the system, power quality is gaining increasing attention and it has to include some other aspects like harmonic distortion, short time transients, unbalances, interruptions and flickers in addition to initial requirements [2, 3].

There are some IEEE and IEC standards such as IEC 61000, En 50160, IEEE 519, about power quality [1, 4, 5]. Nevertheless, IEEE standards do not provide structured and comprehensive discussions on power quality in comparison to IEC standards, but IEEE and IEC both have standards for this special topic, and it is a proof to the importance of power quality issues in modern power systems [1, 4, 6, 7]. A comparison between IEEE and IEC standards for power quality topics is presented in [8, 9].

Power electronic devices as a part of today's grid may have some undesirable effects on grid parameters, power quality, and system reliability. These devices that are commonly used in modern networks have a direct impact on power quality of the distribution networks [10, 11]. An example of these pollutants is inverter-based DGs, which use power electronic devices as an interface to connect to the grid. The important point is the increasing growth of DG implementation both by individuals and electrical utilities. Nevertheless, in standalone usages the output voltage and current of DGs could be improved in the source of generation by means of some inverter switching methods, it is worth noting that because of these capabilities, multilevel inverters are one of the most interesting inverters for applying these switching methods, such as harmonic elimination methods [12-16]. By the increasing penetration of DGs in today's grid, power quality issues become more important and paying attention to this topic is inevitable. Several researches are done on minimizing the negative effects of power electronic based DGs in microgrids using DGs, although this seems to be the first versions of the multi-functional DGs concept, still much improvement has to be done in this area [17-21]. During the years, many devices are suggested as PQI devices, though each one is having some disadvantages, then the research has to continue on this topic yet. Although the integration of power electronic based converters and nonlinear loads may also deteriorate the power quality on the other hand multifunctional DGs are one of the new solutions for power quality enhancement challenge [22]. The microgrid gives us the opportunity to deal with some system problems, making the grid more reliable and secure. The concept of microgrid was first introduced in the 1990s, and then it got more attention from researchers [23].It has special characteristics that will lead to power quality improvements; one of these characteristics is including several units of DG with different natures to increase the overall system reliability. Since most of the employed DG units use power electronics based converters, these energy sources could be utilized for power quality enhancement [24]. Each power electronics based converter used in microgrids is a potential of power quality improvement device, even though it has some other functions as an ordinary converter. Several researches are done in the field of power quality improvement in distributed power systems by date but mostly in a particular field and not comprehensive [2, 3, 9, 25-34]. Power quality includes several aspects, in some of the papers researchers are trying to control voltage in a centralized and decentralized way using DG inverters locally [35, 36]. Different converter topologies and control methods are applied to microgrids to enhance power quality[37, 38]. Since not all of them could be referred in this part, these methods will be explained more in the other sections. To verify the proposed control methods an standard and a testbed for microgrid was needed, then the first version of microgrid testbed was formed to test the control strategies [39, 40]. Since it is a popular research field, there are several well-known testbeds made by several research groups all over the world for microgrid tests [41-44]. In this paper, almost all of these methods have been classified, while paying special attention to multifunctional DGs, both in the local and regional state. First of all these devices will be classified based on the capabilities, to make it comprehensive a brief discuss is done on each device including its operation, advantages,disadvantages, and new applications of each one. Finally, a thorough comparison is done between all these methods taking every aspect into account to make a clear overview of power quality improvement devices

2. Classification of PQI devices

PQI devices could be categorized to three main generations that are developed during last fifty years, the first generation of PQI devices, is simple and reliable in structure and usually do not cost so much, these devices include passive, active and hybrid power filters and will be discussed in section 2.1. The second section of this paper is explaining the working principles,advantages, and disadvantages of the second generation of PQIs which are the most favorite PQIs used in power systems up to now. Finally, the most detailed discussion in this paper is oriented around multi-functional PQIs including smart impedance, electrical springs and multi-functional DGs. Several comparison tables are presented, to show the superiority of each device to the others.

2.1 The first generation of PQI Devices

The first generation of PQI devices mainly focuses on intercepting harmonics from spreading to the grid or being injected to a load or compensating the harmonics mainly on the consumer side. This classification includes passive and active power filters which originated the hybrid power filters, which will be discussed in section 2.1.3

2.1.1 Passive Power Filters

Passive power filters were developed by a combination of inductances and capacitances, to reduce or eliminate current harmonics and compensate reactive power. Fig. 1- c displays a simplified scheme of passive power filters.

Passive filters are categorized in two kinds of parallel and series. These Filters are installed in parallel with loads to make a Detour for the harmonic currents, by setting the inductance and capacitance value as shown in Fig. 1-c, such that in fundamental frequencies the filter has a high impedance and in desired harmonic frequencies it has a very low impedance to absorb the harmonic currents [45, 46]. The other kind of passive power filters is installed in series with load to stop the harmonic current to enter the load. Besides the advantage of being simple and cheap and highly reliable, there is the disadvantage of the need for a new design for every new case, the filters should be tuned to a specific harmonic to act correctly and may lead to over voltage during low power demand. It is worth noting that these filters are used nowadays in some application beside disadvantages because of being simple design and cos-effectiveResearch in the application and novel methods to design of this filter is still going on in three phase and single phase power systems, although most of them are some hybrid applications of filters to reduce the costs and increase the reliability of the system [33, 47-56].

2.1.2 Active Power Filters (APF)

Since tuned passive filter efficiency is highly dependent on the tuned factor, quality factor and source equivalent impedance, active power filters are a good alternative for them. Active power filters were developed to overcome passive filters drawbacks, APFs can reduce harmonics, compensate and improve power factor, compensate unbalances and flicker and regulate voltage. APFs have been used as PQI devices with different topologies and control strategies , [57-62]. There is some detailed comparison between various APFs and the applications of each one, while most of the comparisons are from topology aspect [26, 27, 29]. Active power filters are divided into two main groups, shunt active power filters and series active power filters [63, 64]. The new generation of APFs which deals with the idea of resistive APF (R-APF), will be discussed more in section 2.3.4.1. It is worth noting that a comprehensive comparison is done between advantages and disadvantages of each of these devices in Tables 4 and 5.

2.1.2.1 Shunt active power filter

It compensates current harmonics by injecting a harmonic current with the same magnitude but with 180 degrees phase in difference with the harmonic current. Hence, harmonic current is compensated and grid current is nearly sinusoidal and in phase with source [65]. Furthermore, active power filter can be used to compensate reactive power if proper control methods are used. From the viewpoint of grid, a parallel active power filter with nonlinear load seems like a linear load. Fig. 1-b is a simple display of shunt active power filters, as it is shown APF is compensating the nonlinear load current by injecting the same nonlinear current that load absorbs from the grid, so that the grid current will be sinusoidal [66, 67] Ongoing researches in this field are concentrated over novel control methods of shunt active power filters and also new applications for shunt APFs [68-80]. More detailed analysis of main topologies of shunt active power filters is done in [81].

2.1.2.2 Series active power filter (SAPF)

Although series active power filter (SAPF) was developed longtime ago, it is popular nowadays. It compensates the voltage harmonics by adding a harmonic voltage to the grid in series, with opposite phase with voltage harmonic and acts like a controlled voltage source. It can also compensate voltage unbalances. The main disadvantage of SAPF is that, since series active power filter needs to produce the same power to compensate harmonics, it becomes rather expensive in high power applications. As it can be seen in Fig. 1-a, a series active filter usually connects to the grid by means of a transformer. A series active filter can be used with a shunt passive filter to lower the costs to form hybrid active power filter which will be discussed in detail in 2.1.3. [67, 82, 83]. Deployment of SAPF in various new applications is one of the popular research fields in SAPF [84-87]. Moreover, research on different control strategies for SAPF is going on yet [88-90].

2.1.3 Hybrid active power filters

The hybrid filters have advantage of both active and passive filters in many aspects such as price, efficiency and reliability. Hybrid active power filters offer a method to overcome the physical limits of tuned passive filters and at the same time, reduce cost of using an expensive high capactiy active power filter [91-93]. The main categories of hybrid filters are shunt active series passive filters [67, 94-101], shunt active shunt passive filters [26], and series active shunt passive filters[96, 97]. A simple configuration of hybrid APF is presented in Fig.1-d. Each of these categories has its advantage, disadvantage, application and several detailed studies have been done on this subject [102-104]. The main advantage of these filters in comparison with passive filters is introduction of virtual active resistance and virtual active inductance concept, which can be defined as “virtual active impedance” concept and is discussed in details in [105]. Defining new applications for hybrid filters always has been popular [85, 90, 106]. Some researchers are interested in virtual hybrid APFs, that is an APF between an AC and DC micro-grid [107]. To research finding novel control strategies to improve the performance of hybrid filters has always been popular for researchers [108-113].

2.2 The second generation of PQI Devices

Some other methods of harmonic compensation are used in literature; these methods are kind of active power filters using ultra capacitors or renewable energy sources as power sources for controlling power flow to grid. These methods can be classified as the second generation of PQI devices including dynamic voltage restorer (DVR), static VAR compensator (SVC), static compensator (STATCOM), automatic voltage restorer (AVR) and uninterruptible power supply (UPS). There is a slight difference between the operation of these devices, a brief discussion about the operation and capabilities of these devices are provided in each section.

2.2.1 Dynamic Voltage Restorer (DVR)

Dynamic Voltage Restorer (DVR) is a power electronic based device that protects critical loads from voltage unbalances and as shown in Fig. 1-e, it is connected in series with the sensitive load and can absorb or get P and Q from the grid. The working principle of DVR is such that it senses a voltage unbalance in the grid and adds a voltage to grid to compensate it, so it needs an energy storage source that can be a battery, capacitor, ultra capacitor, super conductive energy storage (SMES) and flywheel [114]. Nowadays in many applications RES plays the role of storage sources, in this case not only it can improve the power rating of DVR but also it will decrease the storage source cost. It is worth noting that there is a slight different between these devices and the multi-functional DGs that will be discussed in 2.3.3 that can do both of the roles of power delivery source and PQI device. An isolated transformer is inevitable in DVR structure to isolate the DC and AC side and to protect the device over fault conditions of the grid [115]. While some researchers try to present novel DVRs with different transformer topologies, others research on transformer fewer DVR topologies [116, 117]. Researchers try to improve the performance and rating of DVR by using some kind of novel multilevel inverters and new control strategies in DVR topologies because of the unique characteristics that multilevel inverters will bring to power systems [118-121].

2.2.2 Automatic Voltage Regulator (AVR)

The automatic voltage regulator is a device that is changing the output voltage to keep the critical load voltage at a sufficient level, and it does it by changing the transformer tap or other methods, mechanically or electronically [122].

There are two major groups of AVRs, static AVR and rotary (servo motor AVRs) that tracks the voltage tolerances continuously. The response time of AVR in rotary ones is not so little to give the AVR ability to track every change in voltage and on the other hand, static AVRs that are power electronic based devices and faster than servo motor AVRs, having less precession on tracking voltage tolerances because of the discrete voltage change of these AVRs. Nowadays different algorithms are used to design the AVRs and improve the performance of these devices, some of these algorithms and a comparison between classic design methods and new design methods are explained in more details in [123-128].

2.2.3 DSTATCOM

Distribution static VAR compensator is a kind of device that is widely used in industry and distribution system, capable of regulating load voltage by absorbing or giving reactive power to it. There are two different VAR compensators, TCR and TSC that are thyristor-controlled reactors and thyristor-switched capacitors. DSTATCOM is a kind of static VAR compensator (SVC) that is equipped with a voltage source inverter to regulate the output voltage continuously unlike SVC that is regulating the output voltage discontinuously. As the configuration of SVC is shown in Fig. 1-f, it can inject or absorb reactive power from loads [129].

2.2.4 UPS

The uninterruptible power supply is a power electronic based device that can sense voltage and frequency unbalance, under or over voltages and supply the critical load by itself with a pure sinusoidal voltage and a fixed frequency. Due to physical classification of UPS, there are two major types; static and dynamic UPSs, static UPSs are made up of power electronic switches while the other group may have some rotary parts like a flywheel, there is also a combination of these two types that is called hybrid UPS. Based on international standards IEC 62040-3 and ENV 500091-3 and application point of view, there are three types of UPSs, offline (passive standby or line preferred) UPSs, line-interactive UPS, and online (double conversion or inverter preferred) UPSs [130-133]. To understand the main difference between these UPSs, a comparison is presented in Table 1. As it can be seen from the table Online UPS are capable of solving all the mentioned problems, while line-interactive UPSs are only able to deal with brown out and long time over voltages, and finally, off-line UPSs can deal with short time (>10ms) sag, swell and total black-outs. The main drawback of static UPSs is the need for large energy storage, though it feeds the whole load in the case of unbalance, not a part of it like DVR [131-134]. Nowadays some researches are going on application of UPS as an active power filter to overcome storage size problem of UPSs. Some other researchers are trying to develop improved control strategies for UPS systems [135-137]. Other researches are done on improving design concept of modern UPS systems[138-140]. Research on standards, qualifications and reliability of UPS systems has always been popular, e.g. IEEE has recently published an updated version of UPS and battery charger standard [141, 142].

2.3 The third generation of PQI Devicess

Next generation of power quality improvement equipment is mostly multi-functional, which are capable of doing more than one task at the same time with the same hardware that will lead to increased cos-effectiveness, besides being reliable and effective. Characteristics of all aforementioned topologies could be gathered in a novel topology called “smart impedance” [143-145]. Electrical spring is another device of this group that performs voltage regulation while improving the stability of grid and also takes part in demand response program [146-149]. The most improved class of these devices is multi-functional DGs which are getting more and more attentions nowadays and researchers are proposing novel control methods to improve the functionality of these devices.

2.3.1 Smart impedance

As it was mentioned earlier, hybrid and active power filters helped on improving the physical parameters of tuned passive filters just in one aspect. By combination of an active converter, a coupling transformer, a capacitor bank and an appropriated control strategy, in single phase or three phase topology the concept of “Smart Impedance” is formed. It can solve the tuning process of passive filters since all the tuning process is done automatically. It can compensate harmonic current, harmonic unbalances, improve quality factor, tuned factor and displacement power factor [143, 145]. In weak systems like microgrids that source impedance is not negligible, the smart impedance can also help improving voltage regulation and stability. Its control strategy is based on proportional resonant controller, by means of which, power system synchronization is possible in the absence of phase locked loops. As it is obvious, smart impedance firstly was formed as an improved tuned passive filter that leads to optimal tuning factor and quality factor [143] but its working principles are different. It can behave as different equivalent impedances due to its working mode both in fundamental and harmonic frequencies. Smart impedance can perform as a shunt active filter, series active filter, a tuned passive filter, a capacitor bank and a combination of an active and passive filter to reduce the capacity of filters moreover it can mitigate selected harmonics of interest. For example, smart impedance can act like a short circuit (zero impedance) for load current harmonics, or it can act like infinite impedance against undesired harmonics, at the same time in fundamental frequency it can act the actual needed impedance to improve load displacement power factor [150]. It can be told that smart impedance is a variable impedance and can take different values due to system needs and power quality improvement.

Fig. 2 describes a simple smart impedance topology, as it can be seen, power circuit is composed of a capacitor bank connected to a power converter via a transformer, and three control blocks are formed on the basis of the proportional resonant (P + Resonant) converter to alleviate system current harmonics without need for PLL. The harmonic control block is used to eliminate harmonics using P+Resonant controller, while Displacement power factor (DPF) block can control injected reactive power by capacitor bank and DC voltage control block regulates DC link voltage of each converter [151, 152].

2.3.2 Electrical springs

Concept of electrical spring was developed on the basis of mechanical spring principles; it can also be used as a voltage regulator and in the case of integrating into electrical appliances, it can act as a smart load (as it is shown in Fig. 3) [153], which can follow the power generation profile. By means of the distributed smart loads in electrical power system, stability of power system will increase independently of the communication system and information [146]. If a power system could be imagined as a mattress, and subsidence of mattress as voltage drops all over the network, using mechanical springs to avoid mattress subsidence is somehow identical to using electric springs to avoid voltage drops and help improving voltage stability, this concept could be better understood by details in [147, 148, 153, 154]. Its most important advantage is that by the failure of few springs systems stays stable. Electrical spring would store energy and pay it back to the power system in the case of need, and therefore it can alleviate stability problems of renewable energy sources.

Like mechanical springs, electrical springs can do these three tasks in a power system, 1) to store (electrical) energy; 2) to support voltage regulation; 3) to abate electrical system oscillations and act as inductance and capacitance as presented in equations (1) and (2). In equation (1), q is the amount of stored electrical charge in capacitor, V_a is the voltage on Capacitor, and i_c is the current following through capacitor. Electrical springs have been improved and new generations of ESs named ES2 and ES3 are presented in [153, 154] with some novel capabilities such as P & Q compensation and harmonic reduction.

Equation (1) presents that voltage regulation process is affected by the amount of stored charge in capacitor and equation (2) reveals the direct relation between stored charge and current and the fact that stored charge can be managed by a controlled current source.

$$q = \begin{cases} q = CV_a & Inductive\,\mathrm{mode}\,e \\ q = -CV_a & capacitive\,\mathrm{mod}\,e_a \end{cases} \qquad (1)$$

$$q = \int i_c \, dt \qquad (2)$$

To damp the electrical oscillations a non-critical electrical load (such as water heating or refrigerator) should be connected in series with lossless spring to form a “smart load”, it can dissipate electrical energy for damping objective, and also it can help the spring follow the generation profile of power system. This feature of electrical spring is useful in improving voltage stability of future adaptive power system that deals with intermittent renewable energy sources [148].

Fig. 4 represents a simplified power distribution system with critical and non-critical loads, electric springs and the simulated mechanical behavior of springs to lift the voltage dips is also shown in Fig. 4. What a mechanical spring does in a mattress is to support the subsides, electrical springs do the same to a power system by supporting the power system with regulating the voltage and preventing under voltages and over voltages. Unlike non-critical loads, critical loads are loads requiring regulated voltage such as control boards and medical equipment.

Electrical spring is like a reactive power controller that controls input voltage instead of output voltage, and in contrast with other reactive power controllers such as FACTS or SVCs that only take part in reactive power compensating, it can manage both reactive and active power. It can produce a sinusoidal voltage named V_a that is perpendicular with I_o, and it can be controlled 90 degrees lagging or leading to I_o. As shown in equation (3) sum of V_a and V_o is equal to main voltage V_s [149].

$$\overrightarrow{V_a} + \overrightarrow{V_o} = \overrightarrow{V_s} \qquad (3)$$

Fig.5 is an example of vector diagram of an electric spring that operates in inductive mode, and it can be concluded that V_o is controlled by increasing and decreasing of V_a, so it is capable of controlling the amount of reactive power that non-critical load consumes, then it can also be called as a demand response solution [155].

Recently feasibility of using ES in DC microgrids has also been reported in [154, 156]Previous solutions were not suitable for DC microgrid problems. DC-ES is serially connected to non-critical load forming the smart load and it has a bi-directional DC-DC power converter and storage elements such as batteries in its structure. Power system oscillations can be damped by means of non-critical load and storage sources and therefore demand response becomes operational in DC microgrids [154].

2.3.3 Multifunctional DGs

Nowadays, demands for renewable energy sources are increasing for different reasons, most of these energy sources output DC Voltage and this source of power needs to be converted to AC in order to be used. Although there are some researches on control, management, development, power quality improvement, utilization of DC microgrids and some home appliances compatible with DC electricity has been developed but it is not as inclusive as AC grids [157-161]. Power electronic converters are an inevitable part of these systems but there is a problem, and it's the overall cost of these systems that creates doubt in cost-effectiveness of power electronic based RESs. To make these sources cos-effective it is possible to add ancillary services for converters in power systems such as being an active power filter or an energy storage source for different smart grid applications.Therefore these kinds of RESs are called multifunctional RESs (MFRES) and will have great part in future smart grids. MFRESs can be categorized by the effecting domain or by some objects to be controlled. Both of these categories will be discussed and different control methods will be presented for different objectives [162-164].

2.3.4 Control methods of MFRESs

Some of the MFRESs can influence just a part of power system locally, while others can affect more than a part or region. There are little differences in the control methods, in a way that local systems only consider the output current of RES to be harmonic free, while regional MFRES may consider the whole area as a unique region and treat it as a linear load, in this case, objective will be the voltage of PCC or grid current. For this reason, multiple control methods can be used to control the inverters of MFRES, including current control method (CCM) [165-169], voltage control method (VCM) [162, 170, 171] and hybrid control method (HCM) [38, 172, 173] that will be discussed further. The Overall scheme of harmonic compensation in micro-grids is shown in Fig. 6 and it will be explained more in 2.3.4.1.

As it was mentioned above, to control the MFRES, multiple methods are implemented in themicrogrids, and usually these methods are hierarchal [43, 174-180]. Multiple levels of control are applied to the microgrids, including energy management, load supervision, voltage and current control in primary control level, power quality issues including power flow control and synchronization with grid in secondary control level and finally in tertiary control level, economic dispatch, DSM and microgrid supervision are the focus areas [181]. The other popular control method in this area is Model predictive control or direct control that could be utilized in harmonic compensation and power quality improvement and active power filter applications because of its good dynamic response and simplicity of the controller [70, 182-184]. In the next section, there will be a detailed discussion of the two control levels [185] as the third control level is not the focus area in the field of this paper. MFRES are considered to participate in load sharing as well as PQI roles, and the main objectives related to PQI services are harmonic compensation of PCC voltage, local load current, and DG output current compensation. How to fulfill these objectives in the microgrids are discussed in detail by three different control methods in the following sections.

2.3.4.1 Current control method

The current control method is the most common method to control grid connected DGs, and it has an increasing penetrate in grid-connected microgrids, Fig. 7 explains the control strategy for CCM, it is obvious that, DG unit in this method, compensates current harmonics as well as participating in load sharing of themicrogrid. It compensates the line current harmonic as default compensating object of CCM and two other compensation modes to be discussed are PCC voltage harmonic compensation and local harmonic compensation. The main control scheme of CCM is shown in Fig 8.

In PCC voltage harmonic compensation, the basic idea is to provide nonlinear load current by DG and grid current will only include sinusoidal currents and as a result PCC voltage will be harmonic free since the nonlinear load current is provided by DG [37, 165-168, 186].

Because of the distributed nature of the nonlinear loads, it is difficult to directly compensate the nonlinear load, another method based on measurement of local current uses the resistive active power filter (R-APF) concept {Akagi, 1997 #123;Bai, 2018 #438} in which DG unit works like a small damping resistor at the selected harmonic frequencies. As it is obvious in Fig 7, there are two different control levels, controlling fundamental power and Harmonic power delivered to microgrid.

To fulfill Local load harmonic compensation, the DG unit should absorb the local load current harmonics, when this method of compensation is applied, microgrid including DG unit and the nonlinear load is seen as a linear load source from the grid point of view. The difference between how to implement PCC voltage harmonic compensation and local load harmonic compensation lays in setting the DG unit current reference for CCM controller that is shown in Fig 9 .In PCC voltage harmonic compensation, a current reference is calculated as follows.

$$\begin{aligned} I_{ref} &= I_{ref\_f} + I_{ref\_h} \\ &= I_{ref\_f} - H_D(s).V_{PCC}/R_V \end{aligned} \qquad (4)$$

In which, I_{ref_f} is the fundamental DG current reference that controls *P* and *Q* and how to calculate it is explained in fig 7, R_V is the equivalent DG resistor at harmonic frequencies and $H_D(s)$ is the harmonic detector to extract PCC harmonic voltage.

For the local load harmonic compensation, current reference is set to:

$$\begin{aligned} I_{ref} &= I_{ref\_f} + I_{ref\_h} \\ &= I_{ref\_f} + H_D(s).I_{local} \end{aligned} \qquad (5)$$

In which I_{Local} is the local load current, it’s obvious that for DG line current harmonic rejection, the reference current is;

$$I_{ref} = I_{ref\_f} \qquad (6)$$

It should be mentioned that when compensating PCC voltage, some other disturbances may be added to system. Since the objective is to have a harmonic free PCC voltage, it can be ignored. It is correct for other kinds of compensations, and this is called the whack-a-mole effect, then a tradeoff should be done due to optimization of harmonics in a microgrid and all aspects of power quality should be taken into account [188].

2.3.4.2 Voltage control method

Nowadays most grid-connected inverters use CCM to control power flow, but VCM is also popular for some reasons. Since it can mimic the behavior of a synchronous generator [162, 189-191] and on the other hand for independent microgrids, VCM is a proper choice to control frequency and voltage. By means of droop control and deriving a suitable voltage reference, VCM enables decentralized control of multiple DGs for demand sharing without need to communication systems [171, 172, 192-195]. It would hardly control the output current harmonics of a DG since it does not have a closed loop line current regulation so the output current is highly sensitive to PCC voltage disturbances and local load harmonics. It can be enhanced by means of virtual harmonic impedance. An overall view of VCM based DG control schematic is shown in Fig. 10, here droop control is used to derive the instantaneous voltage reference. As for CCM method, several objectives can be obtained by VCM as well, which are discussed in the following.

For PCC harmonic compensation, voltage reference should be calculated as (7), where $H_D(s)$ is the harmonic detector, τ is the feed forward gain, and V_{Ref} is the modified voltage reference.

$$\begin{aligned} V_{ref} &= V_{ref\_f} + V_{ref\_\mathrm{h}} \\ &= V_{ref\_f} - H_D(s).V_{PCC} \end{aligned} \tag{7}$$

And the corresponding equivalent impedance $Z_{DG,eq}$ is calculated by equation (8).

$$Z_{DG,eq} = Z_{DG} / (1+\tau) \tag{8}$$

Where $Z_{DG} = SL_2 + R_2$ is the LCL filter grid-side inductance. DG acts as a small impedance at selected harmonics. Like a resistive active power filter (R-APF) with a small impedance of $Z_{DG,eq}$ and a high feed-forward gain, PCC harmonic specifications could be improved. Virtual harmonic impedance that is shown in the equations (7) and (8) can take inductive or resistive values due to Selected feed forward gain τ, such that $Z_{DG,eq}$ can be inductive when τ is a real number and it has resistive nature when supposing τ as a complex number, to accurately control the amount of virtual impedance, grid-side information is needed and it is a drawback for this control system.

Local load harmonic compensation cannot be realized by the references provided in (7) and to compensate local load harmonic a harmonic current feed forward term should be added to the inner control loop reference. On the other hand, it needs a high-bandwidth inverter output current tracking and the inner controller of VCM G_{Inner} should be changed to a method such as the Hysteresis control, model predictive control or multiple harmonic resonant controllers but it may increase the complexity of control method and bring some drawbacks to VCM [196, 197]. To overcome some of these drawbacks, researches are going on to decrease the computational burdens of the inner control loop.

To apply DG line current harmonic rejection when using VCM, value of τ should be considered -1, So that DG acts like a big virtual harmonic impedance in harmonic frequencies, rejecting harmonic currents from I_{DG} and flowing harmonic currents to the grid, It is somehow similar to what is done in CCM controlled DG without any harmonic compensation system, so thanks to series virtual harmonic impedance, line current of DG can be harmonic free, a detailed explanation of this system can be seen in Fig. 11 [195].

2.3.4.3 Hybrid control method

There is another method of control for DG inverters called as HCM, in this method both fundamental capacitor voltage and line harmonic current is controlled. Like VCM, the output power of DG is controlled by regulating the fundamental capacitor voltage in HCM and ; line current harmonics can be controlled by means of a closed-loop harmonic current compensator. Control diagram of HCM is shown in Fig 12. Fig 13 also explains the main control unit of HCM, multiple control terms are included in this controller, the first term is a resonant controller in fundamental frequencies controlling fundamental capacitor voltage, the second one is the line current harmonic controller that is composed of multiple resonant controllers that work in different harmonic frequencies, and finally the third one is an active damping term that is made up of a proportional controller and can provide a damping path for both capacitor voltage control and line harmonic current control. Equation (9) shows the reference voltage to control the DG inverter, and it is obvious that by this reference voltage and other arrangements done in this control method, the output voltage of DG, and line current harmonics can be controlled separately [172, 195, 198]. It is easy to compensate the PCC voltage harmonics by just setting the current reference of DG inverter to (4), just like what is done in CCM method.

$$\begin{aligned} V_{out}^{*} &= G_{power}(s).(V_{ref\_f} - V_C) \\ &+ G_{harmonic}(s).\,(I_{ref\_\mathrm{h}} - I_{DG}) \\ &+ G_{damping}(s)\ I_{Ind} \end{aligned} \tag{9}$$

In this case, DG acts like a small virtual impedance at the selected harmonic frequencies to absorb the harmonic currents, making PCC voltage harmonic free. As the current reference for HCM is the same as for CCM, then I_{ref_h} is calculated just as the one explained about CCM in Fig. 7, even though there are some advantages in using HCM method that will be mentioned in next section.

When HCM is used to compensate local load harmonics, it is able to provide some unique benefits, if I_{ref_h} in (9) is replaced by harmonic content of local load currents, most of the harmonics produced by local loads can be compensated and a harmonic free I_{MG} will be delivered to PCC. Since the harmonic current control loop has a small gain for fundamental frequencies, measured local load I_{Local} by itself can be considered as I_{ref_h} for controlling harmonic current without using harmonic extractor block $H_D(s)$ in HCM. Harmonic compensation by this method has a great benefit over CCM and VCM, and it makes HCM attractive and cost-effective for controlling medium scaled DG units' inverters with limited computational power. It should be noticed that, active damping element has only a proportional controller that influences both the fundamental voltage control path and the harmonic current control path. The detailed operation of each compensation method is given in the following sections.

To compensate PCC voltage harmonics with HCM, harmonic current reference should be set as in (4) ($I_{ref\_h} = H_D(s).(V_{PCC} / R_V)$). In this case, DG unit works as a small virtual resistive impedance at the selected harmonic frequency and can easily compensate PCC voltage harmonics in a similar way like CCM method.

To locally compensate the load current with HCM, it is possible to set the I_{ref_h} in (9) to local load harmonic current. This term will control the DG unit to compensate local load current harmonics leaving an improved I_{MG} to the PCC. Since the local load harmonic compensation loop has a small gain in fundamental frequency, there is no need to use a harmonic extractor block to obtain harmonic load current and the measured line current I_{Local} can represent the harmonic current. Then it can be used as the current reference I_{ref_h} in (9), this is an outstanding characteristic of this method that gives preference to HCM in comparison with other methods.

It is possible to reject DG harmonic current by setting a proper reference current for DG controller. If I_{ref_h} is set to zero, most of the DG harmonic current is rejected. It is somehow like CCM, where DG current is fully sinusoidal and main grid provides all harmonic current of the nonlinear loads.

The other advantage of HCM is that it can be used instead as CCM by simply replacing the first term (9) with the fundamental current. So the fundamental and harmonic currents can be controlled separately but in this case, as a characteristic of HCM there is no need for harmonic extraction block in local load harmonic compensation. Finally, a brief comparison is presented in Table. 2 to verify the capabilities of each method in satisfying the objectives of controlling DG units. Afterward, a brief comparison of advantages and disadvantages of each method is presented in Table. 3. Each of control methods has benefits over the others but there should always be a tradeoff between complexity of control, easy implementation and costs. When there is no need to have control over voltage there is no need to handle control complexity of HCM instead of using simple CCM, or when it is related to stand alone microgrids, maybe VCM is the best option. Fig 14 presents a classification of PQI devices by considering the functionality and development year also.

2.3.5 Harmonic current sharing among DGs

For harmonic sharing between multiple DGs, when multiple DG units are responsible for harmonic compensation, it should be divided between DGs in relation bae on the DG compensation capacity. For example, when compensating PCC voltage harmonic by means of several DG units, the virtual impedance of each DG should be in reverse proportion to its available current for compensating. It is simple to use the virtual resistor to share harmonic currents between multiple DGs by means of the hierarchal controller. Although this method needs a low band-width communication system to transmit data such as the value of the virtual resistor and therefore it is somehow unreliable in the case of communication unavailability [152, 173, 175]. There is an alternative for this method to use droop control in steady state control of harmonic current sharing as a secondary control which is needless of communication system [199, 200].

When it is up to practical use of these compensation methods to share harmonic currents between multiple DGs, some other important factors have an effect on the harmonic sharing process, such as location of sensitive loads, feeder power losses, economical dispatch, existing active/passive harmonic filters and voltage regulators. To have the best harmonic current sharing between multiple DGs, considering these factors, an optimization in setting value of virtual impedance is essential [201, 202]. Although some other consideration should be taken into account. For example, it is important that in the case virtual impedance is not supposed fully resistive, the phase angle of multiple virtual impedances should be equal to avoid circulating current between DGs [171, 203].

A thorough comparison of different PQI devices introduced up to date is presented in Table. 4. Almost all of these devices can regulate the grid voltage and some harmonic compensation besides P and Q compensation but some of these capabilities are unique between PQIs such as Selective harmonic compensation (SHE) and load feeding. Finally, it should be noted that using multifunctional DGs will increase the cost efficiency of using DGs, on the other hand, it helps improving distribution system power quality without the need to add other utilities to the grid. In the future, it will be essential to create conditions that not only the grid side but also the utility and DG owners benefit from using DGs for improving distribution system power quality.

Another detailed comparison between PQI devices is presented in Table. 5, in this table two aspects are added in comparison columns, as distributed PQI nature and cos-effectiveness. Distributed PQI nature refers to the case that a PQI device is distributed all over the grid, this state not only depends on its capability and size but also depends on its cost. Hybrid filter can be installed all over the grid but it may cost a lot and it is not effective, so hybrid filter does not qualify as a distributed PQI device, as a contrary MFDGs will be an inevitable part of future grids, and because almost no hardware is installed other than theRES control converters, it seems to be more cos-effective than devices like APF, STATCOM and SVC. In this table cos-effectiveness index 1 refers to the cheapest PQI device in comparison to its capabilities, So MFDGs may have the highest cos-effectiveness index due to not adding expensive hardware to microgrid and many capabilities these devices will add to a microgrid.

3. Conclusion and Future Trends

In this paper,in-depth analysis and comparison is done between different methods of distribution power system power quality improvement methods that have been introduced till now. To do so, a timeline figure of these devices is provided that is categorized into three main generations, every generation of PI devices include several devices for which applications, advantages and disadvantages are explained. Because of the growing popularity of renewable energy sources main concentraion of this paper was on reviewing the methods which have been applied to control the multi-functional DG units. In this regard, different control methods of inverter-based renewable energy sources are studied in detail by considering the effecting domain and application. Advantages and disadvantages of each method are exposed. Finally, a thorough comparison is done between DPQI (distributed power quality improvement) methods introduced up to now.

Since the future power electrical grids are moving toward smaller, renewable energy based microgrids, the concentration on the power quality issues of these microgrids is inevitable, so far several of these devices has been introduced and used but as the costs increase, power electronic converters play an important role in decision making for the future grid technologies. For cost affordable PQI in distribution level, maybe the best option is to use some multi-functional devices such as MFDGs, but there are several issues to be considered, like communication and online metering as an important part of control methods, or maybe trying some new control methods independent or at least, less dependent on communication and online metering. So improvements in infrastructures of smart electricity grid such as communication devices with online metering and monitoring will take a great amount of researchers' concentration. Another concern could be the computational limit of PQI devices in the past, but as the computational limits of controllers are going up by time, it may seem reasonable to get much of the computational capabilities of controllers to improve the operation of the microgrids without considering it as a limit, an example of this is the application of model predictive control in power electronics in last years. To add some levels of extra reliability to microgrids and PQI issues, adding some storage devices or UPS systems will be a good idea, since maintaining these storage sources will be costly, so storage device operation improvement could be also a future trend. New generations of UPS systems which can help improve the power quality without feeding total load power may be a possible solution.

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